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# Search for squarks and gluinos in events with jets and missing transverse energy in $p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV

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The results of a search for squarks and gluinos using data from  $p\bar{p}$  collisions recorded at a center-of-mass energy of 1.96 TeV by the DØ detector at the Fermilab Tevatron Collider are reported. The topologies analyzed consist of acoplanar-jet and multijet events with large missing transverse

energy. No evidence for the production of squarks or gluinos was found in a data sample of  $310 \text{ pb}^{-1}$ . Lower limits of 325 and 241 GeV were derived at the 95% C.L. on the squark and gluino masses, respectively, within the framework of minimal supergravity with  $\tan\beta = 3$ ,  $A_0 = 0$ , and  $\mu < 0$ .

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Supersymmetric models predict the existence of spin-0 quarks, or squarks ( $\tilde{q}$ ), and spin-1/2 gluons, or gluinos ( $\tilde{g}$ ), as partners of the ordinary quarks and gluons. Supersymmetric particles carry a value of  $-1$  for  $R$ -parity, a multiplicative quantum number, while  $R = 1$  for standard model (SM) particles. If  $R$ -parity is conserved, as assumed in the following, supersymmetric particles are produced in pairs. Their decay leads to SM particles and to the lightest supersymmetric particle (LSP), which is stable. In supersymmetric models inspired by supergravity [1], the commonly accepted LSP candidate is the lightest neutralino ( $\tilde{\chi}_1^0$ , a mixture of the superpartners of the neutral gauge and Higgs bosons), which is weakly interacting, thus escaping detection and providing the classic missing transverse energy ( $\cancel{E}_T$ ) signature at colliders. The most copiously produced supersymmetric particles in  $p\bar{p}$  collisions should be, if sufficiently light, colored particles, *i.e.* squarks and gluinos. If squarks are lighter than gluinos, they will tend to decay according to  $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ , and their pair production will yield an acoplanar-jet topology with  $\cancel{E}_T$ . If gluinos are lighter than squarks, their pair production and decay via  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$  will lead to topologies containing a large number of jets and  $\cancel{E}_T$ .

In this Letter, a search for squarks and gluinos in topologies with jets and large  $\cancel{E}_T$  is reported, using  $310 \text{ pb}^{-1}$  of data collected at a center-of-mass energy of 1.96 TeV with the DØ detector during Run II of the Fermilab Tevatron  $p\bar{p}$  Collider. The search was conducted within the framework of the minimal supergravity model (mSUGRA) [1]. Previous direct mass limits are 195 GeV for gluinos if squarks are very heavy, and 300 GeV for squarks and gluinos of equal masses [2, 3].

A detailed description of the DØ detector can be found in Ref. [4]. The central tracking system consists of a silicon microstrip tracker and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet. A liquid-argon and uranium calorimeter covers pseudorapidities up to  $|\eta| \approx 4.2$ , where  $\eta = -\ln[\tan(\theta/2)]$  and  $\theta$  is the polar angle with respect to the proton beam direction. The calorimeter consists of three sections, housed in separate cryostats: the central one covers  $|\eta| \lesssim 1.1$ , and the two end sections extend the coverage to larger  $|\eta|$ . The calorimeter is segmented in depth, with four electromagnetic layers followed by up to five hadronic layers. It is also segmented in projective towers of size  $0.1 \times 0.1$  in  $\eta - \phi$  space, where  $\phi$  is the azimuthal angle in radians. Calorimeter cells are defined as intersections of towers and layers. Additional sampling is provided by scintillating tiles in the regions at the bound-

ary between cryostats. An outer muon system, covering  $|\eta| < 2$ , consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers after the toroids. Jets are reconstructed from the energy deposited in calorimeter towers using the Run II cone algorithm [5] with radius  $\mathcal{R} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.5$ . The jet energy scale (JES) is derived from the transverse momentum balance in photon-plus-jet events. The  $\cancel{E}_T$  is calculated from all calorimeter cells, and corrected for the jet energy scale and for reconstructed muons.

The DØ trigger system consists of three levels, L1, L2, and L3. The events used in this analysis were recorded using a jet trigger requiring missing transverse energy calculated using the sum of the jet momenta ( $\cancel{E}_T = |\sum_{\text{jets}} \vec{p}_T|$ ). At L1, events were required to have at least three calorimeter towers of size  $\Delta\phi \times \Delta\eta = 0.2 \times 0.2$  with transverse energy  $E_T$  greater than 5 GeV. Events with a large imbalance in transverse momentum were then selected by requiring  $\cancel{E}_T$  to be greater than 20 GeV and 30 GeV at L2 and L3 respectively. In a small fraction of the data sample recorded at a higher instantaneous luminosity, the acoplanarity, defined as the azimuthal angle between the two leading jets, was required to be less than  $168.75^\circ$  and  $170^\circ$  at L2 and L3 respectively.

The signal consists of jets and  $\cancel{E}_T$ . This topology also arises from SM processes with real  $\cancel{E}_T$ , such as  $p\bar{p} \rightarrow Z + \text{jets}$  with  $Z \rightarrow \nu\bar{\nu}$ , and from multijet production when one or more jets are mismeasured (QCD background). Simulated events from SM and mSUGRA processes were produced using Monte Carlo (MC) generators, subjected to a full GEANT-based [6] simulation of the detector geometry and response, and processed through the same reconstruction chain as the data. The CTEQ5L [7] parton density functions (PDF) were used, and a Poisson-average of 0.8 minimum bias events was overlaid on each simulated event. The QCD background was not simulated, but estimated directly from data. To simulate  $W/Z + \text{jets}$  and  $t\bar{t}$  production, the ALPGEN 1.3 generator [8] was used, interfaced with PYTHIA 6.202 [9] for the simulation of initial and final state radiation and of jet hadronization. The next-to-leading order (NLO) cross sections were computed with MCFM 3.4.4 [10], or taken from Ref. [11] for  $t\bar{t}$  production.

Squark and gluino production and decay were simulated with PYTHIA. The masses and couplings of the supersymmetric particles were calculated with ISAJET 7.58 [12] from the set of five mSUGRA parameters:  $m_0$  and  $m_{1/2}$ , which are universal scalar and gaugino masses, and  $A_0$ , a universal trilinear coupling, all defined at the scale

of grand unification;  $\tan\beta$ , the ratio of the vacuum expectation values of the two Higgs fields; and the sign of the Higgs-mixing mass parameter  $\mu$ . To retain consistency with earlier analyses [2, 3], the following parameters were fixed:  $A_0 = 0$ ,  $\tan\beta = 3$ , and  $\mu < 0$ . For the same reason, the production of scalar top quarks, or stops, was ignored. In the following, “squark mass” stands for the average mass of all squarks other than stops. All squark and gluino decay modes were taken into account in the simulation, including cascade decays such as  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0$  with  $\tilde{\chi}_2^0 \rightarrow \ell^+\ell^-\tilde{\chi}_1^0$ . The NLO cross sections of the various signal processes were calculated with PROSPINO 2 [13].

Three benchmark scenarios have been considered. At low  $m_0$ , the gluino is heavier than the squarks, and the process with the dominant cross section is  $\tilde{q}\bar{q}$  production. A “dijet” analysis was optimized to search for events containing a pair of acoplanar jets. At high  $m_0$ , the squarks are much heavier than the gluino, and the process with the highest cross section is therefore  $\tilde{g}\tilde{g}$  production. A “gluino” analysis was optimized to search for multijet events ( $\geq 4$  jets). In the intermediate  $m_0$  region, all squark-gluino production processes contribute to the total cross section, in particular the  $\tilde{q}\tilde{g}$  process becomes relevant. A “3-jets” analysis was optimized to search for events with at least three jets. The benchmark for this analysis is the case where  $m_{\tilde{q}} = m_{\tilde{g}}$ .

A common event preselection was used for the three analyses to select events with at least two jets and substantial  $\cancel{E}_T$  ( $\geq 40$  GeV). The acoplanarity was required to be below  $165^\circ$ . The longitudinal position of the primary vertex with respect to the detector center was restricted,  $|z| < 60$  cm, to ensure an efficient primary vertex reconstruction. The two leading jets, *i.e.* those with the largest transverse energies, were required to be in the central region of the calorimeter,  $|\eta_{\text{det}}| < 0.8$ , where  $\eta_{\text{det}}$  is the jet pseudorapidity calculated under the assumption that the jet originates from the detector center. These jets must have their fraction of energy in the electromagnetic layers of the calorimeter smaller than 0.95. Minimum transverse energies of 60 and 40 GeV were required for the first and second leading jets, respectively.

The tracking capabilities of the Run II DØ detector were used to significantly reduce the QCD background. A comparison of the jet energy with the energy carried by its associated charged particles was performed. In particular, the ratio  $CPF$  of the transverse momentum carried by tracks associated with the jet to the jet  $E_T$  is expected to be close to zero if an incorrect primary vertex was selected. The two leading jets were required to have  $CPF$  larger than 0.05.

Different selection criteria were next applied in the three analyses, as summarized in Table I. In the “dijet” analysis, the cut on the second jet  $E_T$  was raised to 50 GeV. In the “3-jets” and “gluino” analyses, a third and fourth jet were required, respectively. They must fulfill

TABLE I: Selection criteria for the three analyses (all energies in GeV); see the text for further details.

Preselection Cut	All Analyses		
$\cancel{E}_T$	$\geq 40$		
Acoplanarity	$< 165^\circ$		
Vertex $z$ pos.	$< 60$ cm		
Selection Cut	“dijet”	“3-jets”	“gluino”
1st jet $E_T^a$	$\geq 60$	$\geq 60$	$\geq 60$
2nd jet $E_T^a$	$\geq 50$	$\geq 40$	$\geq 40$
3rd jet $E_T^a$	—	$\geq 30$	$\geq 30$
4th jet $E_T^a$	—	—	$\geq 20$
Electron veto	yes	yes	yes
Muon veto	yes	yes	yes
$\Delta\phi(\cancel{E}_T, \text{jet}_1)$	$\geq 90^\circ$	$\geq 90^\circ$	$\geq 90^\circ$
$\Delta\phi(\cancel{E}_T, \text{jet}_2)$	$\geq 50^\circ$	$\geq 50^\circ$	$\geq 50^\circ$
$\Delta\phi_{\min}(\cancel{E}_T, \text{any jet})$	$\geq 40^\circ$	—	—
$H_T$	$\geq 275$	$\geq 350$	$\geq 225$
$\cancel{E}_T$	$\geq 175$	$\geq 100$	$\geq 75$

<sup>a</sup>Jets subject to an  $E_T$  cut are also required to be central ( $|\eta_{\text{det}}| < 0.8$ ), with an electromagnetic fraction below 0.95, and to have  $CPF \geq 0.05$ .

the same quality criteria as the two leading jets, except for the  $E_T$  cuts which were set at 30 and 20 GeV. In all three analyses, a veto on isolated electrons or muons with  $p_T > 10$  GeV rejects a large fraction of events originating from the  $W/Z$ +jets processes. The azimuthal angles between the  $\cancel{E}_T$  and the first jet,  $\Delta\phi(\cancel{E}_T, \text{jet}_1)$ , and the second jet,  $\Delta\phi(\cancel{E}_T, \text{jet}_2)$ , were used to remove events where the energy of one jet was mismeasured, generating  $\cancel{E}_T$  aligned with that jet. The cuts are  $\Delta\phi(\cancel{E}_T, \text{jet}_1) \geq 90^\circ$  and  $\Delta\phi(\cancel{E}_T, \text{jet}_2) \geq 50^\circ$ .

In the “dijet” analysis, QCD events were further suppressed by requiring that the minimum azimuthal angle  $\Delta\phi_{\min}(\cancel{E}_T, \text{any jet})$  between the  $\cancel{E}_T$  and any jet with  $E_T > 15$  GeV be greater than  $40^\circ$ . Because of the higher jet multiplicity, this criterion was not used in the “3-jets” and “gluino” analyses.

The “dijet”  $\Delta\phi_{\min}(\cancel{E}_T, \text{any jet})$  cut along with the two final cuts on  $H_T = \sum_{\text{jets}} E_T$  and on  $\cancel{E}_T$  were optimized by minimizing the expected upper limit on the cross section in the absence of signal. To this end, as well as for the derivation of the final results, the modified frequentist  $CL_s$  method [14] was used. For each set of cuts tested, the QCD background contribution was estimated from an exponential fit to the  $\cancel{E}_T$  distribution below 60 GeV, after subtraction of the SM background processes, extrapolated above the chosen  $\cancel{E}_T$  cut value. The optimal cuts thus determined are given in Table I for the three analyses. Figure 1 shows: the  $\Delta\phi_{\min}(\cancel{E}_T, \text{any jet})$  distribution after applying the “dijet” analysis criteria with a  $\cancel{E}_T$  cut reduced to 80 GeV and without requiring the conditions on  $\Delta\phi_{\min}(\cancel{E}_T, \text{any jet})$  itself and on  $\Delta\phi(\cancel{E}_T, \text{jet}_2)$ ; the  $H_T$  distribution after applying all the “3-jets” analysis criteria except the one on  $H_T$ ; and the  $\cancel{E}_T$  distribution after applying all the “gluino” analysis criteria except the



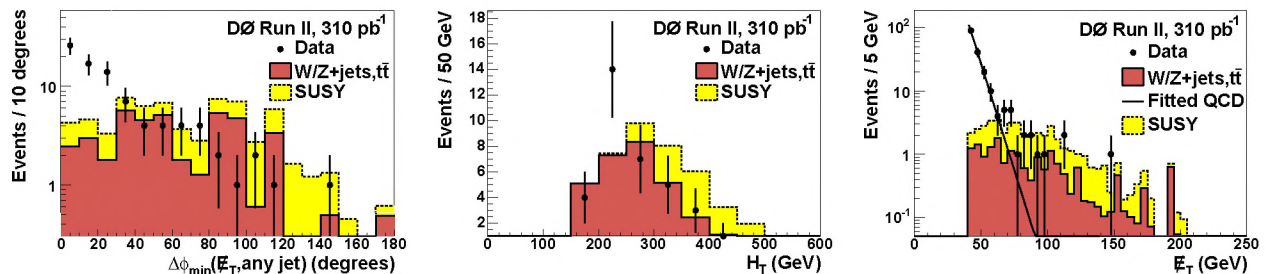


FIG. 1:  $\Delta\phi_{\min}(\ell_T, \text{any jet})$  distribution after applying the “dijet” analysis criteria with a  $\ell_T$  cut reduced to 80 GeV and without requiring the conditions on  $\Delta\phi_{\min}(\ell_T, \text{any jet})$  itself and on  $\Delta\phi(\ell_T, \text{jet}_2)$  (left),  $H_T$  distribution after applying all the “3-jets” analysis criteria except the one on  $H_T$  (middle), and  $\ell_T$  distribution after applying all the “gluino” analysis criteria except the final one on  $\ell_T$  (right), for data (points with error bars), for non-QCD SM background (full histogram), and for signal MC (dashed histogram on top of SM). For each analysis, the signal drawn is the one for the appropriate benchmark scenario (Table II). In the  $\ell_T$  distribution, the fitted QCD background is also drawn.

TABLE II: For each analysis, information on the signal for which it was optimized:  $m_0, m_{1/2}, m_{\tilde{g}}, m_{\tilde{q}}$  and nominal NLO cross section, signal efficiency, the number of events observed, the number of events expected from SM and QCD backgrounds and the 95% C.L. signal cross section upper limit. The first uncertainty is statistical and the second is systematic.

Analysis	$(m_0, m_{1/2})$ (GeV)	$(m_{\tilde{g}}, m_{\tilde{q}})$ (GeV)	$\sigma_{\text{nom}}$ (pb)	$\epsilon_{\text{sig.}}$ (%)	$N_{\text{obs.}}$	$N_{\text{backgrd.}}$	$\sigma_{95}$ (pb)
“dijet”	(25,145)	(366,318)	0.63	$6.2 \pm 0.4^{+1.1}_{-0.9}$	6	$4.8^{+4.4}_{-2.0} {}^{+1.1}_{-0.8}$	0.44
“3-jets”	(191,126)	(330,330)	0.64	$4.7 \pm 0.3^{+0.8}_{-0.7}$	4	$3.9^{+1.3}_{-1.0} {}^{+0.7}_{-0.8}$	0.45
“gluino”	(500,80)	(240,507)	2.41	$2.3 \pm 0.2^{+0.4}_{-0.3}$	10	$10.3^{+1.5}_{-1.4} {}^{+1.9}_{-2.5}$	1.72

one on  $\ell_T$ .

The numbers of events selected by each analysis are reported in Table II, as well as the numbers of background events expected. Six events were selected by the “dijet” analysis, four by the “3-jets” analysis, and ten by the “gluino” analysis. The total expected background contributions are 4.8, 3.9 and 10.3 events, respectively. The main background contributions are from  $Z \rightarrow \nu\bar{\nu} + \text{jets}$ ,  $W \rightarrow l\nu + \text{jets}$ , and  $t\bar{t} \rightarrow b\bar{b}q\bar{q}'l\nu$ . The QCD background was evaluated from a fit to the  $\ell_T$  distribution as described above. It was found to be negligible in the “dijet” and “3-jets” analyses, and was therefore conservatively ignored. A QCD contribution of  $0.7^{+0.7}_{-0.4}$  event was estimated in the “gluino” analysis. The uncertainties were obtained by taking into account the accuracy of the fit parameter determination and by varying the range of the fit. The signal efficiencies are given in Table II for the three benchmark scenarios, with the corresponding values of  $m_0, m_{1/2}$ , the squark and gluino masses, and the NLO cross section. The quoted systematic uncertainties are discussed below.

The uncertainty coming from the JES corrections is one of the most important. It is typically of the order of 13% for the SM backgrounds and 10% for the signal efficiencies. The uncertainties on the jet energy resolution, on the jet track confirmation, and on the jet reconstruction and identification efficiencies were evaluated. They

lead to systematic uncertainties of 3.5%, 4.0% and 5.4% in the “dijet,” “3-jets,” and “gluino” analyses, respectively. The trigger was found to be fully efficient for the event samples surviving all analysis cuts. Conservatively, a 2% uncertainty was set on the trigger efficiency. The uncertainty on the determination of the luminosity is 6.5% [15]. All of these uncertainties are fully correlated between signal and SM backgrounds. A 15% systematic uncertainty was set on the  $W/Z + \text{jets}$  and  $t\bar{t}$  NLO cross sections. The uncertainty on the signal acceptance due to the PDF choice was determined to be 6%, using the forty-eigenvector basis of the CTEQ6.1M PDF set [16].

The signal cross sections are very sensitive to the PDF choice and to the renormalization and factorization scale,  $\mu_{\text{rf}}$ . The nominal NLO cross sections,  $\sigma_{\text{nom}}$ , were computed with the CTEQ6.1M PDF and for  $\mu_{\text{rf}} = Q$ , where  $Q$  was taken to be equal to  $m_{\tilde{g}}$  for  $\tilde{g}\tilde{g}$  production,  $m_{\tilde{q}}$  for  $\tilde{q}\tilde{q}$  and  $\tilde{q}\tilde{q}'$  productions, and  $(m_{\tilde{q}} + m_{\tilde{g}})/2$  for  $\tilde{q}\tilde{g}$  production. The uncertainty due to the choice of PDF was determined using the full set of CTEQ6.1M eigenvectors, with the individual uncertainties added in quadrature. The effect on the nominal signal cross sections, which varies between 15% and 50%, is dominated by the large uncertainty on the gluon distribution at high  $x$ . The effect of the renormalization and factorization scale was studied by calculating the signal cross sections for  $\mu_{\text{rf}} = Q$ ,  $\mu_{\text{rf}} = Q/2$  and  $\mu_{\text{rf}} = 2 \times Q$ . The factor

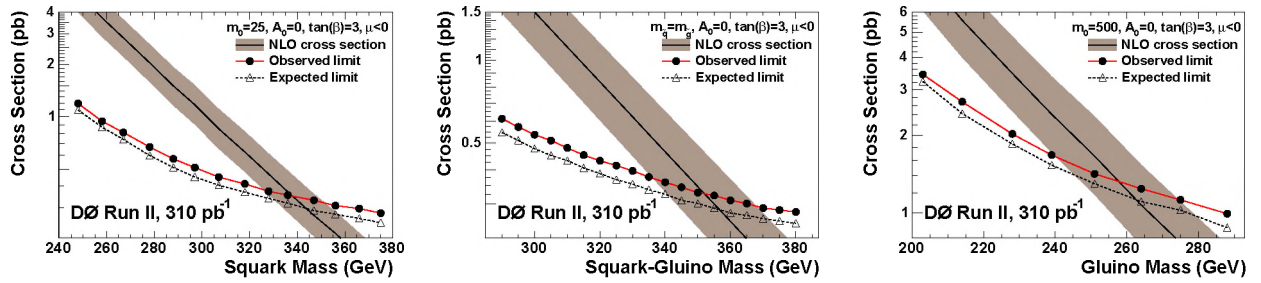


FIG. 2: For  $\tan\beta = 3$ ,  $A_0 = 0$ ,  $\mu < 0$ , observed (closed circles) and expected (open triangles) 95% C.L. upper limits on squark-gluino production cross sections combining the analyses for  $m_0 = 25$  GeV (left),  $m_{\tilde{q}} = m_{\tilde{g}}$  (middle), and  $m_0 = 500$  GeV (right). The nominal production cross sections are also shown, with shaded bands corresponding to the PDF and renormalization-and-factorization scale uncertainties.

two on this scale reduces or increases the nominal signal cross sections by 15–20%. The PDF and  $\mu_{\text{rf}}$  effects were added in quadrature to compute minimum,  $\sigma_{\text{min}}$ , and maximum,  $\sigma_{\text{max}}$ , signal cross sections.

No significant excess of events was observed in the data with respect to the SM background expectation in any of the three analyses. Therefore, an excluded domain in the gluino-squark mass plane was determined as follows. The three analyses were run over signal MC samples generated in the gluino-squark mass plane to compute signal efficiencies. Then, to take advantage of the different features of the three analyses, they were combined in the limit computation, with the small overlaps taken into account. In the data, no events were selected by more than one analysis.

Limits at the 95% C.L. were computed for three hypotheses on the signal cross sections: nominal, minimum, and maximum. Figure 2 shows the observed and expected upper limits on squark-gluino production cross sections for the three benchmark scenarios. For the “3-jets” and “gluino” analyses, the expected limits computed with the numbers of events reported in Table II are almost identical to the observed ones. Once the combination of analyses is performed, the expected limits become slightly better than the observed limits at large  $m_0$  and for  $m_{\tilde{q}} = m_{\tilde{g}}$ , as can be seen in Figure 2.

Figure 3 shows the excluded domain in the gluino-squark mass plane. The absolute lower limits on the squark and gluino masses obtained in the most conservative hypothesis,  $\sigma_{\text{min}}$ , are 325 GeV and 241 GeV, respectively. The corresponding expected limits are 330 GeV and 246 GeV. Table III summarizes these absolute limits as a function of the signal cross section hypothesis. Limits were also derived for the particular case  $m_{\tilde{q}} = m_{\tilde{g}}$ . For  $\sigma_{\text{min}}$ , squark and gluino masses below 337 GeV are excluded, while the expected limit is 340 GeV. The observed limit becomes 351 GeV for  $\sigma_{\text{nom}}$ , and 368 GeV for  $\sigma_{\text{max}}$ .

These results improve on the previous direct limits on squark and gluino masses [2, 3, 17]. They were obtained within the mSUGRA framework with  $\tan\beta = 3$ ,  $A_0 = 0$ ,

TABLE III: Absolute lower limits at the 95% C.L. on the squark and gluino masses (in GeV) as a function of the choice of signal cross section hypothesis as defined in the text. Numbers in parentheses correspond to the expected limits. These limits are valid for the mSUGRA parameters:  $\tan\beta = 3$ ,  $A_0 = 0$ ,  $\mu < 0$ .

Hypothesis	Gluino mass	Squark mass
$\sigma_{\text{min}}$	241 (246)	325 (330)
$\sigma_{\text{nom}}$	257 (261)	339 (344)
$\sigma_{\text{max}}$	274 (280)	352 (358)

and  $\mu < 0$ . A general scan of the mSUGRA parameter space is beyond the scope of the current analysis, but it has been verified that similar results would be obtained for a large class of parameter sets. The limits obtained at LEP on the chargino ( $\tilde{\chi}^\pm$ ) and slepton ( $\tilde{\ell}$ ) masses can be turned into constraints on the mSUGRA parameters  $m_0$  and  $m_{1/2}$  [18], and hence on the squark and gluino masses as shown in Fig. 3. The limits from Higgs boson searches at LEP are even more constraining [18], actually ruling out all of the squark and gluino mass domain to which the Tevatron could be sensitive. The interpretation of these indirect constraints is however more sensitive to the details of the model considered than the direct limits presented here.

In summary, a search for events with jets and large  $\cancel{E}_T$  has been performed in a 310  $\text{pb}^{-1}$  data sample from  $p\bar{p}$  collisions at 1.96 TeV, collected by the DØ detector. Three analyses were designed, specifically targeted to the dijet, three-jet, and multijet topologies. The numbers of events observed are in agreement with the SM background predictions. The results have been interpreted in the framework of minimal supergravity with  $\tan\beta = 3$ ,  $A_0 = 0$ ,  $\mu < 0$ . For the central choice of PDF, and for a renormalization and factorization scale equal to the mass of the squark or gluino produced, the lower limits on the squark and gluino masses are 339 and 257 GeV at the 95% C.L. Taking into account the PDF uncer-



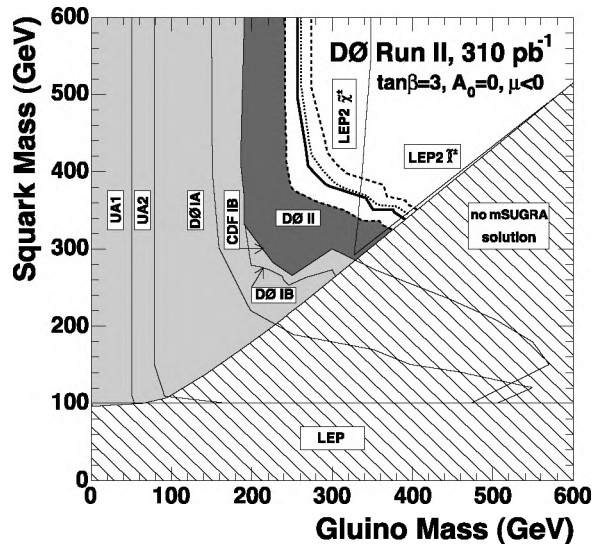


FIG. 3: In the gluino and squark mass plane, excluded regions at the 95% C.L. by direct searches in the mSUGRA framework with  $\tan\beta = 3$ ,  $A_0 = 0$ ,  $\mu < 0$ . The new region excluded by this analysis in the most conservative hypothesis ( $\sigma_{\min}$ ) is shown in dark shading. The thick line is the limit of the excluded region for the  $\sigma_{\text{nom}}$  hypothesis. The corresponding expected limit is the dotted line. The band delimited by the two dashed lines shows the effect of the PDF choice and of a variation of  $\mu_{\text{rf}}$  by a factor of two. Regions excluded by previous experiments are indicated in light shading [2, 3, 17]. The two thin lines indicate the indirect limits inferred from the LEP2 chargino and slepton searches [18]. The region where no mSUGRA solution can be found is shown hatched.

tainties and allowing for a factor of two in the choice of scale, these limits are reduced to 325 and 241 GeV, respectively. These are the most constraining direct limits on the squark and gluino masses to date.

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